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AN IDENTIFICATION OF THE BEST MIXTURE COMPOSITION FOR THE JOULE-THOMSON REFRIGERATOR OPERATING AT 90 K

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ABSTRACT

In recent days researchers have been trying to operate Joule-Thomson refrigerators with mixed refrigerants instead of single refrigerant as operating fluid. Usage of mixtures in the place of single refrigerant is increasing rapidly because of some favourable conditions like achieving high heat transfer coefficients, avoiding of multistage compression units, high overall efficiency of the refrigerator and a mixture of refrigerants gives more pollution free environment. Conventional vapour compression refrigeration system working with chlorofluorocarbon refrigerants will deplete the ozone layer, whereas joule Thomson refrigerators with a mixture of refrigerants will not detrimental to ozone layer hence it is more suitable for a green environment. The present paper discusses the selection of the appropriate mixture for Joule-Thomson refrigerator operating at 90 K in Gas Refrigerant supply (GRS) mode and its effect on the performance of the overall system. It is estimated that the optimization of mixture composition enhances the exergy efficiency from 31.4% to 34 % with a substantial increasein refrigeration capacity.

KEYWORDS: Exergy, Gas Refrigerant Supply, J-T Refrigerator & Mixed Refrigerant

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NOMENCLATURE

Abbreviations

GRS	Gas Refrigerant Supply
HX	Heat Exchanger
LRS	Liquid Refrigerant Supply
SQP	Sequential Quadratic Programming
UL	Upper Limit
LL	Lower Limit
OS	Optimal Solution
DPT	Dew point temperature
IE	Initial estimate
FS	Final solution
PW_c	Power Consumption of the compressor
Q_R	Cooler Refrigeration Capacity
Q_{RO}	Heat Load

Subscripts

Cs	Compressor
Ex	Exergy
J	Joule
K	Kelvin
Min	Minimum
V	Volume

Greek Symbols

η	Efficiency
ξ	Mole Fraction
ΔT	Temperature drop
Δp	Pressure drop
%	Percentage

INTRODUCTION

Cryogenic refrigerators operating with mixtures as working fluids are gaining lots of interest in the recent past because of the absence of multistage compression units and many countries replaced the chlorofluorocarbon refrigerants with different mixture compositions [1]. In addition to this, the mixtures used in refrigeration and liquefaction systems have several advantages like high heat transfer coefficients in the heat exchanger and low-performance diminishing of the heat exchanger because of the longitudinal conduction. But all these are possible if the chosen mixture composition is appropriate [2]. Many methods are available in the literature to select the mixture composition for J-T refrigerators. Alexeev and Quack [3] got the patent for the new gas mixture contains propane, nitrogen, methane, and ethane with different working pressure. Little [4] described a method to choose a mixture for LRS systems with more than four compositions with a temperature range of 130 to 150 K. Dobak et al [5] stated a method for the selection of mixture and its composition that are used in cryosurgical devices with a temperature range of 120 to 270 K. Keeping in view of cooling capacity of J-T Refrigerator, Boiarskii et al [6] stated two completely non similar objective functions to select an appropriate optimized mixture. Based up on the compressor suction and discharge pressure, Gong et al [7] proposed a complex optimization algorithm to select the optimized mixture composition in the range of 80 to 150 K. Ardhakapur et al [8] conducted experiments in a recuperative heat exchanger which is used to precook the refrigerated mixture used in the Joule-Thomson refrigerator. They analysed the temperature distribution along the length of the exchanger and changes in thermo physical properties of the gas mixture. Alexeev et al [9] developed computational model using Hextran software program to investigate the behavior of refrigerant mixture in the heat exchanger of a Joule-Thomson refrigerating system to optimize the design of heat exchanger. Later several researchers extended their studies experimentally and numerically for optimization of mixtures and their composition [10-14]. Few authors [3,4] reported that a selection of mixture composition is done based on better performance and efficiency of the system. But they didn't disclose the values of efficiency in the literature due to because they are confidential patents. Venkatarathnam [2] conducted several numerical studies by varying the mixture composition (Nitrogen, Methane, Ethane & Propane). He stated the system efficiencies as 27% & 32.3%. By replacing ethane with ethylene we achieved the efficiency of 33.5%. This is due to because ethylene is a refrigerant

suitable for very low temperatures also it will not affect the ozone layer and creates a pollution-free environment. The main aim of this paper is to optimize the composition of nitrogen-hydrocarbon mixtures for acquiring higher exergy efficiency in J-T refrigerators operating at an evaporating temperature of 90 K (in GRS mode). Present paper also gives the information about the percentage change in exergy efficiency for various identified mixtures which are not clearly reported by the authors in previous studies operating at evaporating temperature of 90 K (in GRS mode).

METHODOLOGY

Figure 1 shows the schematic diagram of cold section of Joule-Thomson refrigerator working with constituents as Nitrogen-Hydrocarbon mixtures. Point 1 represents the exit of the compressor. The high pressure refrigerant leaving the compressor rejects heat to the low pressure refrigerant exiting from the evaporator before it is expanded in a throttle device. Most of the exergy losses take place in the heat exchanger and throttle device of the J-T refrigeration systems [2]. By choosing the appropriate mixture composition these losses can be minimized, which in turn improves the exergy efficiency. Sequential quadratic (second order) programming method is used to optimize mixture constituents that are presented in the Tables 2, 3 and 4. All the simulations are done using Aspen plus [15]. The thermodynamic properties of the mixture are estimated using Peng-Robinson equation of state [16].

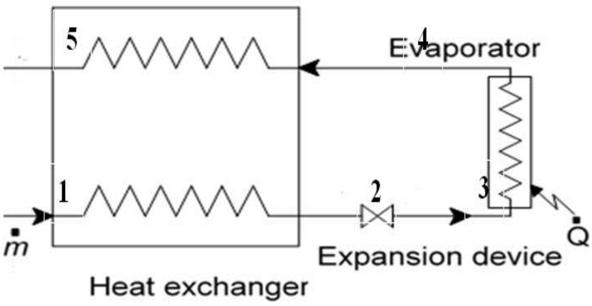

Figure 1: Joule–Thomson Refrigerator Cold Section Operating in GRS Mode

Determination of Losses in Different Components of J-T Refrigerator

In the present analysis, sequential quadratic (second order) programming approach is used to increase the exergy efficiency. It is one of the successful methods to solve the problems, especially where non linearity exists [2]. Thermodynamic modeling of exergy losses are stated below.

$$ex_1 = h_1 - T_{amb}S_1 \tag{1}$$

$$ex_5 = h_5 - T_{amb}S_5 \tag{2}$$

$$Work\ Output = ex_1 - ex_5 \tag{3}$$

$$W = Q\left(\frac{T_{amb}}{T_4} - 1\right) \tag{4}$$

$$Exergy\ efficiency = \frac{W}{Work\ Output} \tag{5}$$

$$Q_{Vol} = \rho_5(h_5 - h_1) \tag{6}$$

$$Exergy\ loss\ in\ expansion\ valve = 100\ \left(\frac{-T_{amb}(S_2 - S_3)}{Work\ Output}\right) \tag{7}$$

$$Exergy\ loss\ in\ Evaprator = \frac{100\left(\left(\left((h_3-h_4)-T_{amb}(S_3-S_4)\right)+Q\left(1-\frac{T_{amb}}{T_4}\right)\right)\right)}{Work\ OutPut} \tag{8}$$

$$Exergy\ Loss\ in\ Heat\ exchanger = 100\,\frac{\left((h_1-h_2)+(h_4-h_5)-T_{amb}(S_1-S_2+S_4-S_5)\right)}{WorkOutput} \tag{9}$$

$$Useful\ effect = (100 - Eq\ (7) - Eq(8) - Eq(9)) \tag{10}$$

Table 1: Methodology for the Optimization of Mixture Composition for the Joule-Thomson Refrigerator Operating at 90 K in GRS Mode (Figure 1)

Design Specifications	
Exergy efficiency of the compressor, $\eta ex, cs$	100%
Volumetric efficiency of the compressor, η_v	100%
Maximum discharge pressure of the compressor, p_1	20 bar
Maximum suction pressure of the compressor, p_5	4 bar
Minimum temperature approach in the heat exchanger, ΔT_{min}	3 K
Objective function: Maximization of Exergy efficiency (η_{ex})	
Subject to Constraints	
Minimum temperature approach between the streams, $\Delta T_{min} \geq \Delta T_{min, specified} = 3$ K	
Condensation should not occur within the aftercooler, or $T_{dew, 1} < T_o$ (300K)	
Design Variables	
Mole fraction of refrigerant gases (ξ)	
Discharge pressure of compressor (p_1)	
Suction pressure of compressor (p_5)	
Temperature of Low-Pressure Refrigerant Leaving the Heat Exchanger (T_5)	
Constants	
Pressure drop in the heat exchanger (high pressure side), Δp_{1-2}	0 bar
Pressure drop in the heat exchanger (low pressure side), Δp_{4-5}	0 bar
Pressure drop in the evaporator, Δp_{3-4}	0 bar

Table 1 gives the objective function, design specifications, design variables, constraints and constants that are used for optimizing the mixture composition. Pressure drops within the heat exchanger and evaporator are assumed to be zero. Compressor suction and discharge pressures are restricted to 4 bar and 20 bar respectively. The minimum temperature approach within the heat exchanger has been chosen as 3 K. All the simulations are carried out by assuming volumetric and exergy efficiencies (under adiabatic conditions) of the compressor to be 100%. Even though compressor efficiency 100% is not possible in reality but still it gives the approximate composition to be charged into the system for better overall efficiency. It is also common practice in literature to assume compressor efficiency to be 100% for the theoretical studies [2].

RESULTS AND DISCUSSIONS

Case 1

Table 2: LL, UL, IE and FS Obtained for Different Design Variables of the Joule-Thomson Refrigerator Operating in a GRS Mode at 90 K (Figure 1)

Design Variable	LL	UL	IE	OS	
Nitrogen	0.01	0.38	0.3	0.292	
Methane	0.01	0.28	0.25	0.174	
Ethane	0.01	0.34	0.25	0.333	
Isobutane	0.01	0.2	0.2	0.2	
Pressure, P_2	14	20	18.4	20	
Pressure, P_1	2	4	3.01	2.98	

Temperature, T_2	80	99	95	93.27	
Stream	1	2	3	4	5
Temperature, K	300	93.27	89.74	90	296.99
Pressure, Bar	20	20	2.98	2.98	2.98
Vapor fraction	1	0	0.0630897	0.1864487	1

Case 2

Table 3: LL, UL, IE and FS Obtained for Different Design Variables of the Joule-Thomson Refrigerator Operating in a GRS Mode at 90 K (Figure 1)

Design Variable	LL	UL	IE	OS	
Nitrogen	0.01	0.4	0.35	0.3272	
Methane	0.01	0.35	0.3	0.1627	
Ethylene	0.01	0.3	0.25	0.3	
Isobutane	0.01	0.21	0.1	0.21	
Pressure, P_2	14	20	18.4	20	
Pressure, P_1	2	4	3.01	4	
Temperature, T_2	80	99	95	93.28873	
Stream	1	2	3	4	5
Temperature, K	300	93.28873	87.38088	90	296.9998
Pressure, Bar	20	20	4	4	4
Vapor fraction	1	0	0.10514	0.1909699	1

Case 3

Table 4: LL, UL, IE and FS Obtained for Different Design Variables of the Joule-Thomson Refrigerator Operating in a GRS Mode at 90 K (Figure 1)

Design Variable	LL	UL	IE	OS	
Nitrogen	0.01	0.4	0.25	0.3272	
Methane	0.01	0.35	0.2	0.18	
Propane	0.01	0.5	0.35	0.426	
Ethylene	0.01	0.25	0.2	0.063	
Pressure, P2	14	20	18.4	20	
Pressure, P1	2	4	4	4	
Temperature, T2	80	99	95	93.13	
Stream	1	2	3	4	5
Temperature, K	300	93.13	86.38088	90	296.9998
Pressure, Bar	20	20	4	4	4
Vapor fraction	1	0	0.112	0.203	1

Table 5: Performance of a Joule-Thomson Refrigerator Operating at 90 K with Optimum Mixture Composition (Table 2, 3 and 4)

Performance parameter	Case 1	Case 2	Case 3
Exergy efficiency (%)	31.43	31.92	33.5
Specific refrigeration effect (J/mol)	633.8	520.8	628.9
Volumetric cooling capacity (J/l)	71.6	86.2	77.9

The Tables 2, 3 and 4 give the LL, UL and OS of the design variables of Joule-Thomson refrigerator operating in GRS mode at 90 K. It also gives the quality of the mixture at different stated points of Joule-Thomson refrigerating system as shown in the Figure 1. From the data presented in the Tables, it is clear that compressor suction pressure is 2.98 bar for case 1 and 4 bar for cases 2 & 3. It is also clear that inlet and outlet of the heat exchanger are in vapor state and entry to the throttle device is in two phases. Low pressure fluid is heated to a temperature of 296.99 K in all the three cases. Table 5

provides the performance data of a Joule-Thomson refrigerator operating at 90 K for optimum mixture composition. A little amount of input exergy is used to meet the useful effect and exergy efficiency which is calculated by using equation 5.

From Table 5 it is observed that exergy efficiency of the system varies from 31.43% to 34% for all the three cases studied. Determination of exergy losses for each and every individual components also carried out by using the equations 7, 8 and 9.

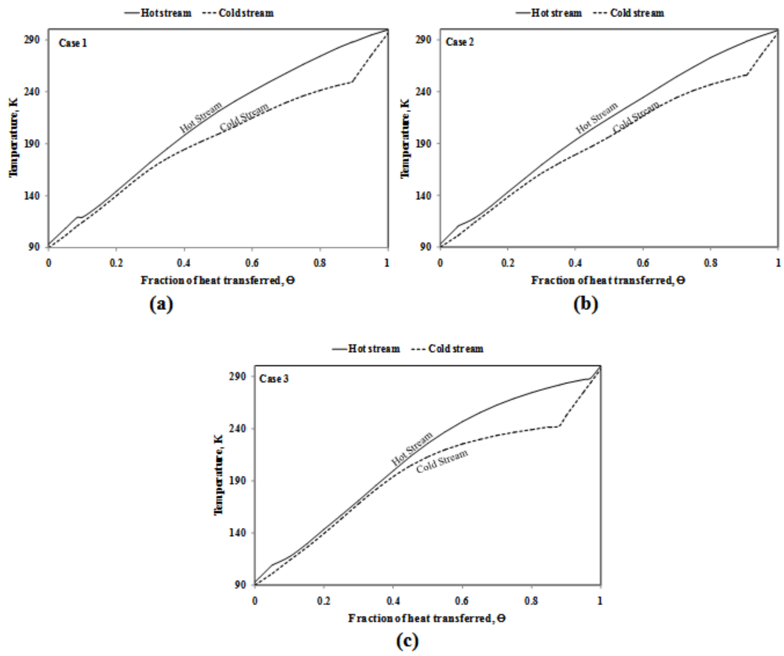

Figure 2: Temperature Profiles of Hot and Cold Streams in the HX for Case 1, 2 and 3

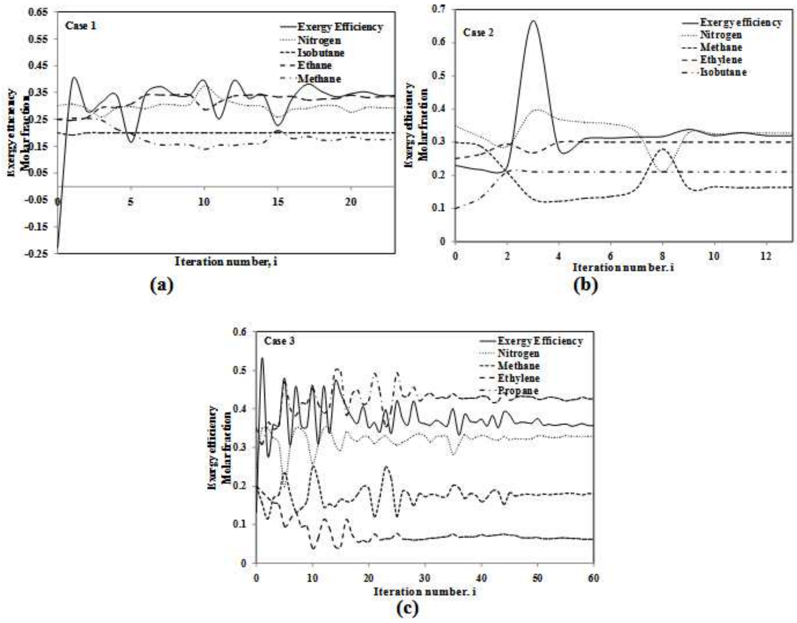

Figure 3: Variation of Design Variables (Composition) and Exergy Efficiency with Iteration Number for Case 1, 2 and 3

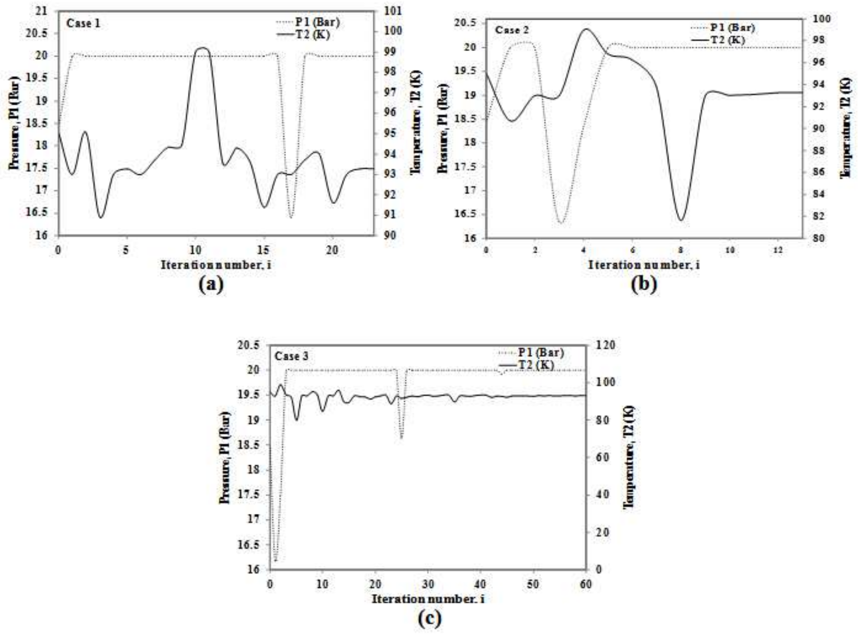

Figure 4: Variation of Design Variables (T2, P_1) with Iteration Number for Case 1, 2 and 3)

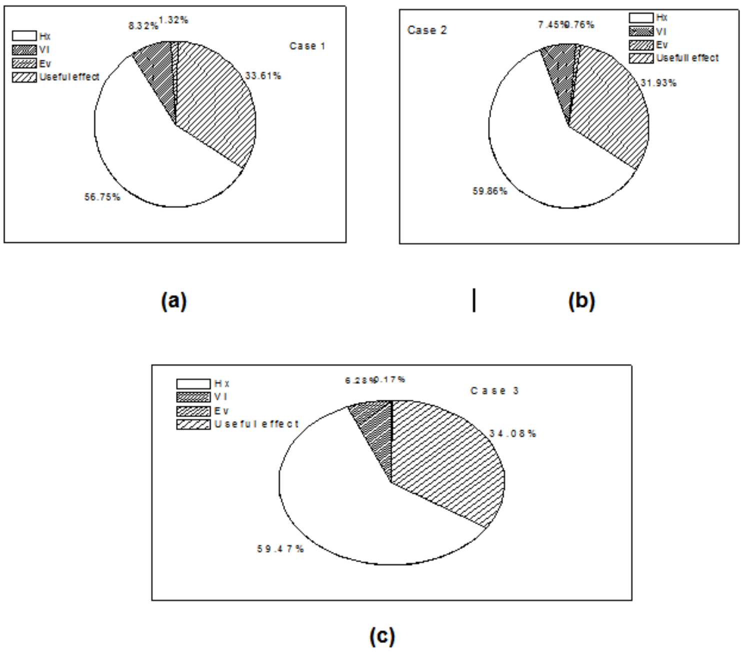

Figure 5: Exergy Losses and Useful Work in J-T Refrigerator in Case 1, 2 and 3

Figure 2 shows the variation of the temperature profile of cold and hot fluid streams across the heat exchangers used in the Joule-Thomson refrigerator. The exergy loss is smaller within the heat exchanger because of smaller temperature differences between the streams and this is possible with the optimum composition of mixtures. From Figure 2, it is evident that the minimum temperature approach occurs at the warm end while the possibility of occurrence of pinch (minimum temperature approach) based mostly on the composition of the mixture. The change of slope in the temperature profile indicates the change of phase of the refrigerant (single to two phases). From Figures 2 to 4, it can be seen that major portion of the temperature profiles (hot and cold stream) in the heat exchanger is parallel specifically in the two phase region of the mixture.

Figure 3 gives the profile of exergy efficiency and the molar concentration of the components of different mixtures. In the case of 1 and 2 composition of Iso-butane and in case 2 composition of ethylene is limited to 0.21 and 0.3 respectively, to ensure that the entry to the heat exchanger is superheated vapour. From the Figure 3, it is also clear that the variation of design variables is non linear and using SQP for optimizing the composition of the mixture is appropriate. In all the three cases, exergy efficiency varies between 31 to 34%. In case 1, exergy efficiency is attained the steady state value of 0.33 after the 15 iterations. In case 2, exergy efficiency is low (0.31) comparing to other two cases, but attains steady state value after 5 iterations. In case 3, exergy efficiency is maximum about 0.34 and attains the steady state value after the 35 iterations only. Hence it is understood that case 3 combination is optimized mixture giving maximum possible exergy efficiency.

Figure 4 shows the variation of compressor discharge pressure and exit temperature of high pressure fluid in the heat exchanger. In all the three cases, compressor discharge is 20 bar to ensure that the compression ratios are within the acceptable limits for the smooth operation of the compressor. The hot fluid exit temperature in the heat exchanger is around 93 K. From Figure 4, it is clearly understood that that number of iterations are more in case 3 for obtaining convergence. Also in case 3, temperature is more or less steady value for all iterations whereas in the other two cases temperature varies randomly.

Figure 5 shows the utilization of input work of the components of different mixtures. A mixture of case 3 possess higher useful effect of 34.08% as compared with case 1 and case 2 and this is due to the addition of higher propane concentration in case 3 which increases the DPT of high pressure refrigerant. Addition of propane also increases the refrigeration effect due to increase in Joule-Thomson coefficient. As a result withincrease in propane content, there is an increase in specific refrigeration effect and exergy efficiency. Because of more exergy loss observed in case 1(in Heat exchanger) it possess less exergy efficiency as compared with other two cases.

CONCLUSIONS

Refrigerators and liquefaction systems using pure nitrogen require very high discharge pressure in the range of 150 to 200 bars, but using the mixture of refrigerants the discharge pressure reduces to 20bar which reduces the work input very much. Optimization of mixture composition of a refrigeration system also improves the exergy efficiency. Good mixture composition ensures that pinch happens at the hotter end of the heat exchanger and inlet to the expansion valve in two-phase, such that exergy losses of these components can be minimized for example in case 3, by mixing the constituents like Nitrogen, Methane, Propane and Ethylene the exergy loss is reduced by 1.5 percent approximately. It is estimated that exergy efficiency attains a maximum value of 34%, for case 3 which is higher than the other two cases. It is also observed that variation of temperature is steady in case 3 whereas it varies randomly in the other two cases. Finally by comparison of all the three cases, case 3 possesses optimized results and it can be identified as a good mixture composition for the Joule Thompson refrigerator operating at 90K.

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